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EXPLORATION AND DEVELOPMENT OF GEOTHERMAL RESOURCES

(With Emphasis on Surface Disturbance)

This report is preliminary and has not been edited or reviewed for conformance with U.S.G.S. standards and nomenclature.

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CONTENTS

Page

Introduction 1
Exploration Techniques 1
  Geological Mapping 1
  Geochemical Studies 1
    Water Sampling 1
    Soil and Rock Analysis 1
  Geophysical Surveys 2
    Gravity Surveys 2
    Magnetic Surveys 2
    Resistivity Surveys 2
    Magnetotelluric Surveys 2
    Radiometric Surveys 4
    Passive Seismic Studies 4
    Active Seismic Studies 4
    Shallow Temperature Holes 5
    Observation Holes 7
Planning an Exploratory or Development Well 7
  Site Selection Criteria 7
  Site Preparation for Drilling 8
    Road Construction 8
    Drill Pad Construction 8
    Drilling Sump Construction 8
Drilling an Exploratory or Development Well 9
  Typical Equipment 9
    Personnel 9
    The Drilling Process 11
    Drilling with Mud 11
    Drilling with Air 11
    Casing Program 12
    Directional Hole 14
    Blowout Prevention 14
    Testing the Well 15
  Abandonment 15
Power Plant Construction 17
Production 19
Mitigating Environmental Impacts 20
Alternative Applications of Geothermal Energy 22
Summary 23
Bibliography 28
Credits for Photos 29

ILLUSTRATIONS

Figure 1. Typical Exploration and Development Sequence 3
2. Typical Shallow Temperature Gradient Hole 6
3. Simplified View of Typical Drilling Site 10

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Page

Figure 4. Typical Casing Program for a Production Well 13
5. Typical Blowout Prevention Equipment 16
6. Typical Abandonment of Exploratory Well 18
7. Simplified view of typical power plant 19

Plate 1. Water Sampling
2. Gravity Survey
3. Magnetic Survey
4. Passive Seismic Studies
5. Active Seismic Study (Explosive Method)
6. Shallow Temperature Gradient Hole
7. Drill Site
8. Drill Site
9. Testing
10. Power Plant
11. Geothermal Field Development
12. The Geysers Field
13. Space Heating
14. Desalination Plant

TABLES

Table 1. Applications of Geothermal Energy in the United States 25
2. Applications of Geothermal Energy Outside the United States 26
3. Temperatures Required for Various Geothermal Applications 27

INTRODUCTION

The discussion which follows briefly outlines the course of action which might be taken by a major operator in the quest for commercial geothermal resources. The steps and methods described are representative of a typical exploration program; contingencies and variations are not within the scope of this paper. The exploration techniques, exploration and development sequences, and types of impacts described in this paper apply to all lands--private, state or Federal. The procedural steps, required forms, and steps for mitigating environmental impacts apply to geothermal operations on Federal lands only. However, procedural requirements may vary on Federal lands administered by different agencies (e.g. National Forest lands, Indian lands, etc.). Therefore, for all proposed geothermal activities involving Federal lands, the appropriate Federal Officer must be contacted for specific information on permits and requirements.

EXPLORATION TECHNIQUES

Initial exploration studies include a review of the literature, broad geologic studies, and the use of available aerial photography or imagery. Favorable regions may then be selected for airborne magnetic surveys. These are not surface-oriented investigations and there is therefore no impact on the region. If results are encouraging, the operator may embark on a program of local reconnaissance. A lease application may also be filed.

Local reconnaissance activities are surface-oriented and will vary in their effects on the environment. All or a combination of the following studies may be made, depending upon the particular area, the experience and exploration philosophy of the operator, and the funds available.

Geological Mapping

Detailed geologic mapping or cursory local reconnaissance may be performed. This may involve some use of existing roads or off-road vehicles. Most of the data is gathered on foot. Hand-size specimens of rock, soil, or spring deposits may be collected for later study or analysis.

Geochemical Studies

Water sampling. An analysis of water from hot springs and other sources can yield valuable information about geothermal temperatures and the origin and composition of geothermal fluids. Samples are collected in small plastic bottles.

Soil and rock analysis. Patterns or "auras" of mineralization may be delineated by the analysis of small (fist-size) soil and rock samples. Age dating analyses may also be performed on some of the rock samples for determination of the most recent magmatic activity.

The above geological and geochemical studies are considered casual use activities. They result in no surface disturbance and, when conducted on Federal lands, do not require leasing or permits. At the completion of this phase the operator has reached the first decision point (see fig. 1). Upon evaluation of the results of his studies he may decide to (1) abandon the project, (2) take necessary steps to acquire a lease, or (3) conduct more intensive and more expensive geophysical exploration. Some of the more intensive exploration methods are described below. All require an approved Notice of Intent to Conduct Geothermal Resources Exploration Operations (Form 3200-9).

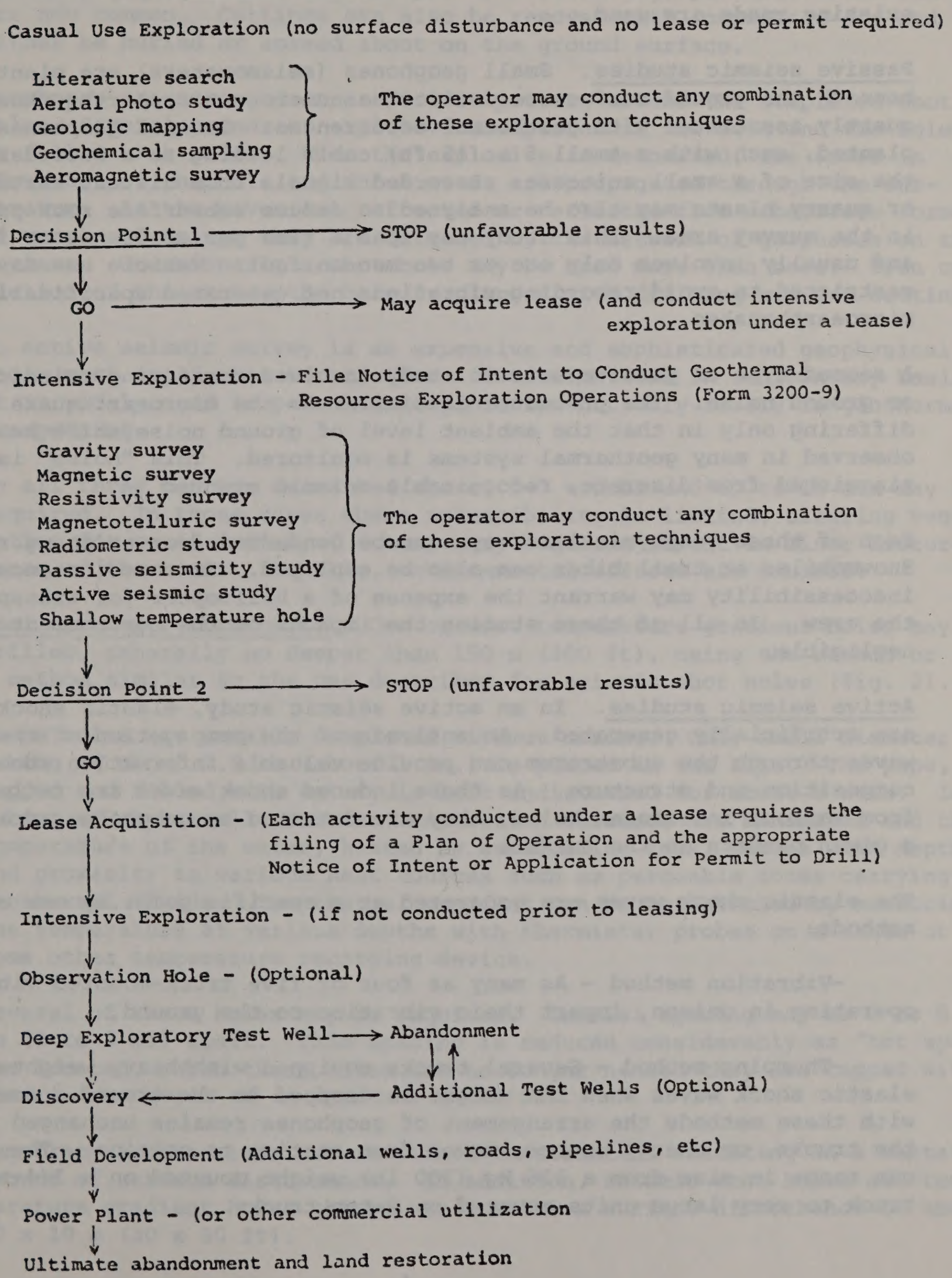
Geophysical Surveys

Gravity surveys. Gravity measurements are made using a hand-carried gravimeter and similarly portable equipment for elevation surveying. Since the density of a material varies with temperature, subtle changes in gravity values over an area may indicate a buried hot rock body or magma chamber. Analyses of these measurements can also provide subsurface structural information, such as inferred fault trends, depths to bedrock, etc. This survey involves a vehicle for transportation and a three-man crew which moves along a predetermined traverse covering the study area. It entails the usage of existing roads and occasional cross-country foot traffic.

Magnetic surveys. Magnetism varies with temperature much as density does. Subsurface rock bodies that exhibit different degrees of magnetism can be mapped by this means. A three-man crew, using a technique similar to that used in gravity surveys, employs a hand-carried magnetometer to measure subtle variations in the magnetic field. A magnetometer may also be mounted on a vehicle which traverses along existing roads. One or two small vehicles may be employed.

Resistivity surveys. The amount of resistance of subsurface materials to the passage of an induced electrical current can indicate much about the subsurface structure. The current is delivered through two widely separated electrodes, which are 1 m (2 to 3 ft) rods driven into the ground up to 3 km (2 mi) apart. Variations in the current transmitted through the ground are recorded by small ceramic potentiometers which receive the current at different locations. This procedure entails the use of two or three small trucks to transport the transmitter and a crew of three to five men. Insulated wires are temporarily strung along the ground and only existing roads need be used.

Magnetotelluric surveys. In magnetotelluric surveys, the natural electrical currents in the earth's crust are measured. As in resistivity surveys, potentiometers placed in different locations record the incoming data and provide valuable information about the subsurface environment. No transmitter is needed and a two-man crew with one vehicle is all that should be required to conduct the survey. Existing roads would be used. There are


Casual Use Exploration (no surface disturbance and no lease or permit required)
Literature search
Aerial photo study
Geologic mapping
Geochemical sampling
Aeromagnetic survey
The operator may conduct any combination of these exploration techniques
Decision Point 1
STOP (unfavorable results)
GO
May acquire lease (and conduct intensive exploration under a lease)
Intensive Exploration - File Notice of Intent to Conduct Geothermal Resources Exploration Operations (Form 3200-9)
Gravity survey
Magnetic survey
Resistivity survey
Magnetotelluric survey
Radiometric study
Passive seismicity study
Active seismic study
Shallow temperature hole
The operator may conduct any combination of these exploration techniques
Decision Point 2
STOP (unfavorable results)
GO
Lease Acquisition - (Each activity conducted under a lease requires the filing of a Plan of Operation and the appropriate Notice of Intent or Application for Permit to Drill)
Intensive Exploration - (if not conducted prior to leasing)
Observation Hole - (Optional)
Deep Exploratory Test Well
Abandonment
Discovery
Additional Test Wells (Optional)
Field Development (Additional wells, roads, pipelines, etc)
Power Plant - (or other commercial utilization
Ultimate abandonment and land restoration

TYPICAL EXPLORATION AND DEVELOPMENT SEQUENCE

FIGURE 1

variations of this survey by which it is possible to probe to different depths (audiomagneto-telluric, telluric current, etc.).

Radiometric surveys. Natural emissions from vents or hot springs may be monitored for radioactive constituents such as radon gas. A hand-held scintillometer is used and, as in each of the above geophysical surveys, existing roads are used.

Passive seismic studies. Small geophones (seismometers) are planted just beneath the ground surface to detect the numerous microearthquakes frequently associated with geothermal occurrences. Several geophones may be planted, each with a small 5 m (15 ft) cable leading to a recorder about the size of a small suitcase. Recorded signals from distant earthquakes or quarry blasts may also be analyzed to deduce subsurface rock properties in the survey area. This study may span a time period of two to four weeks and usually involves only one or two men on foot. Vehicle use may be restricted to avoid recording vibrations not generated specifically by microearthquakes.

A second type of passive seismic study involves monitoring seismic noise or ground noise. The procedure is similar to the microearthquake study, differing only in that the ambient level of ground noise which has been observed in many geothermal systems is monitored. This "noise" is distinguished from discrete, recognizable seismic events.

Each of these geophysical surveys can be conducted from existing roads. Snowmobiles or trail bikes can also be employed. In rare instances inaccessibility may warrant the expense of a helicopter for transporting the crew. In all of these studies the impacts on the environment are negligible.

Active seismic studies. In an active seismic study, elastic shock waves are artificially generated. An analysis of the propagation of these shock waves through the substratum can provide valuable information about its composition and structure. As these induced shock waves are reflected from various interfaces below, they are detected by geophones arranged in a given pattern on the surface.

The elastic shock waves are generated at a specific point by one of three methods:

-Vibration method - As many as four or five truck-mounted vibrators, operating in unison, impart their vibration to the ground.

-Thumping method - Several trucks equipped with heavy weights produce elastic shock waves when the weight is dropped to the ground. Generally, with these methods the arrangement of geophones remains unchanged while the trucks, or energy source, moves from station to station. The equipment can range in size from a 136 kg (300 lb) weight mounted on a 3/4-ton pickup truck to very large units mounted on 3-ton trucks.

-Explosive method - A small rotary drill mounted on a truck is used to drill shallow holes up to a few hundred m (several hundred ft) deep. Several of these 7.5 cm (3 in.) to 13 cm (5 in.) holes may be drilled in one day spaced up to .8 km (½ mi) apart. Water with one or two sacks of gel is generally used as a circulating medium instead of conventional drilling mud. While small mud pits were once dug, portable metal mud pits are now common. Cuttings can also be removed with compressed air and either be buried or spread about on the ground surface.

Geophones are arranged in a specific pattern around the completed shot hole. Several pounds of explosive are placed in the hole and the hole is filled with water. When the explosive is detonated, the water is blown out of the hole and shock waves are propagated through the substratum. As the waves are refracted or reflected from subsurface formations of varying density, they are detected by the network of geophones on the surface. Occasionally a shot hole may be used more than once. Upon completion of the shots, the hole is plugged with drilling mud and cuttings.

An active seismic survey is an expensive and sophisticated geophysical tool, most applicable to structural determinations in sedimentary basins. It is widely used in petroleum exploration but only rarely in geothermal prospecting.

In all three methods described above, 5-7 trucks and up to 15 men may be required. In those cases where accessibility is limited, clearing vegetation for construction of a temporary road can result in minor disturbance of the cover. Usually, environmental effects are minimal.

Shallow temperature holes. One or more temperature gradient holes may be drilled, generally no deeper than 150 m (500 ft), using the method or a method similar to the one described for seismic shot holes (fig. 2).

These holes are usually completed without casing. Only small diameter tubing of about 2.5 cm (about 1 in.) is placed in the hole. The pipe, capped and filled with water, is left undisturbed for about a week. In tubing of such small diameter, convection currents are minimized and the temperature of the water, heated by surrounding rock, varies with depth and proximity to various heat sources such as permeable zones carrying geothermal fluids. The thermal gradient can be established by measuring the temperature at various depths with thermister probes on a cable or some other temperature recording device.

Several of these holes may be required. Initial spacing may be 3 to 8 km (2 to 5 mi) apart. This spacing is reduced considerably as "hot spots" are located. When these holes are no longer needed they are capped with cement to a depth of at least 3 m (10 ft).

Temporary access roads are sometimes constructed, resulting in a certain amount of surface disturbance. In addition, seismic shot holes and temperature gradient holes themselves involve a surface disturbance of about 10 x 10 m (30 x 30 ft).

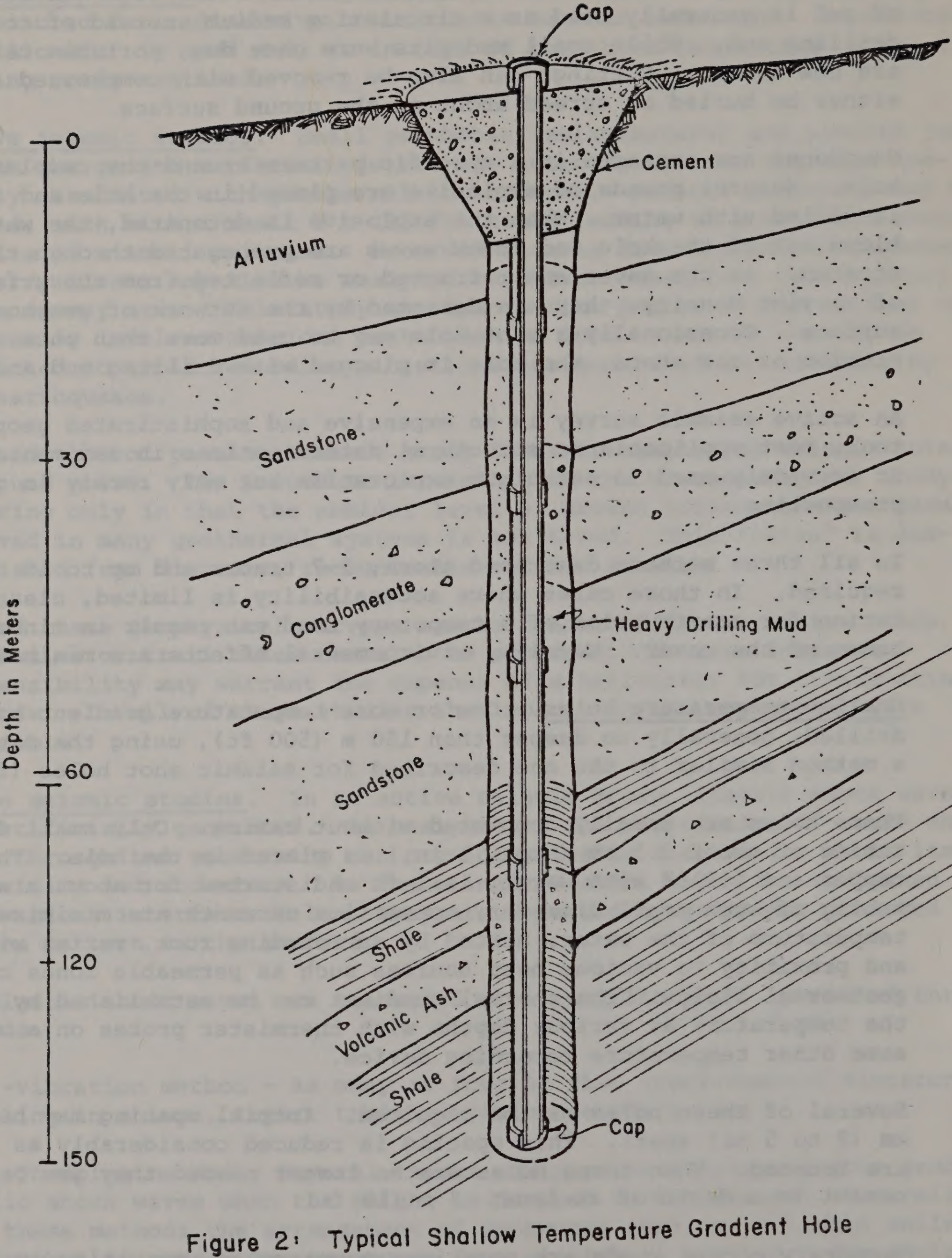


Figure 2: Typical Shallow Temperature Gradient Hole

Determination of temperature gradients represents an excellent but expensive geothermal prospecting technique. Evaluation of results from the shallow temperature gradient hole brings the operator to the second critical decision point (see fig. 1). He must either abandon the prospect, or, if he has not already done so, acquire a lease. After he has obtained a lease he may file a Plan of Operation and the appropriate Notice of Intent to prepare to drill a deep exploratory well. He may also choose to drill observation holes before selecting the final site for his deep exploratory well.

Observation holes. One or more observation holes may be drilled for geologic information and further correlation of subsurface data. Because of the cost and time involved in this phase of exploration, the decision has probably already been made to drill a deep exploratory well. More detailed geologic understanding may be desired for evaluation purposes or for selection of the most favorable site for the exploratory well.

An observation hole can range to .8 km (2,500 ft) or deeper, but drilling stops before a potential reservoir has been penetrated. Due to the greater magnitude of the operation, larger equipment and facilities may be required than that for shot holes or shallow temperature gradient holes. Assuming a fairly deep observation hole is to be drilled, a surface area of about 12 x 18 m (40 x 60 ft) will be cleared and a shallow mud pit, 1 to 2 m (3 to 6 ft) deep, will be constructed with a bulldozer.

A portable rig will drill a 16 to 19 cm (6¼ to a 7½ in.) hole using drilling mud and/or compressed air as a circulating medium. This will require three crews of three men each and intermittent vehicular traffic. When the hole has been satisfactorily drilled and results evaluated, usually within two weeks, the hole is then abandoned in accordance with regulatory requirements. Existing roads are generally used. Jeep trails or fire roads may be cleared and bladed with a bulldozer.

PLANNING AN EXPLORATORY OR DEVELOPMENT WELL

Site Selection Criteria

There are five main factors which will influence the selection of a location for the initial exploratory well. The location of subsequent exploratory wells will naturally be influenced by the results of previous exploratory wells. In the probable order of consideration, they are as follows: (1) legal boundaries - lease agreements must be honored and the lessee must be legally authorized to occupy the surface; (2) environmental suitability - consideration must be given to potential environmental impacts; (3) exploration feedback - site selection will be influenced by the results of the geophysical surveys; (4) geologic criteria - there may be geologic hazards to avoid or geologic factors which help define the target; (5) accessibility - since procedures for moving earth are expensive, sites which require the least preparation are desirable. Rugged terrain and lack of roads therefore do affect site selection when reasonable alternative sites are available.

In selecting a site for a development well, an operator takes into consideration legal boundaries, environmental suitability, geology and accessibility just as he does for exploration wells. In addition, he must consider reservoir characteristics, well spacing, and power plant siting.

Site Preparation for Drilling

The three main facets of site preparation are road construction, drill pad construction, and sump construction.

Road construction. In contrast with the temporary roads required for some of the earlier phases of exploration, roads at this stage are of much better quality. They are designed to carry heavier loads, withstand a much more constant traffic burden, and function year-round if necessary. Steps to achieve this include surfacing the road with rock, gravel or volcanic cinders or mixing oil in with about the first 10 cm (4 in.) of dirt. In hilly terrain, cut and fill construction may be required and a means of surface water runoff must be provided. This can be done by constructing drainage culverts parallel to the road bed and providing drainage conduits where the road "fill" crosses drainage.

Drill pad construction. A drill pad is an area which is leveled and cleared of vegetation. The pad must be large enough to accommodate the drilling rig and accessories, temporary structures, and crew parking. Some maneuvering room must be allowed for service and delivery vehicles. The required surface area, including the reserve pit, generally varies from less than .4 ha (1 acre) to approximately 1.2 ha (3 acres). In hilly regions, pad construction will very likely entail cut and fill techniques. Special care must be taken to insure that unstable geologic conditions do not exist or are not created when these techniques are employed. It is sometimes necessary to surface the pad with rock or gravel where vehicle or foot traffic is heavy.

Drilling sump construction. A waste discharge pit, often called a "sump" is required for the containment of waste fluids and drill cuttings. Since the size of the drilling sump depends on the anticipated depth of the hole, the surface can range from less than a hundred to several thousand square meters and the depth from 1 to 3 m (5 to 10 ft) or more, depending on required volume. Since the drilling sump is designed to contain fluids, special precautions are required to insure impermeability. In all cases, the bottom and sides of the drilling sump will be lined with an impervious material and firmly compacted. In rare instances, the drilling sump may be lined with plastic or sealed with gunite or some similar material. The drilling sump is positioned approximately 10 m (35 ft) from the hole location on the pad so that when the drilling rig is brought in, the drilling sump will be favorably located adjacent to the rig. In a developing field, the same drilling sump may be used for drilling several development wells.

After the road, drilling pad and drilling sump are completed, a 41 to 92 cm (26 to 36 in.) hole is drilled with an auger to a depth of 15 to 30 m (50 to 100 ft) and 46 to 75 cm (20 to 30 in.) conductor pipe is cemented to the surface. The stage is then set to move a rig onto the location and "spud in." In many instances the hole for the conductor pipe is made with the drilling rig.

DRILLING AN EXPLORATORY OR DEVELOPMENT WELL

Typical Equipment

The largest piece of equipment used during the drilling of an exploratory or development well is the drilling rig, which may stand well over 30 m (100 ft) high. The actual drilling assembly is composed of a variety of accessories which are assembled on the location. The accessories, as shown in figure 3, may include (1) the mixing tanks--steel tanks measuring roughly 13x3x2 m (40x8x6 ft), where new drilling mud is mixed with chemicals and used drilling mud is stored after being separated from cuttings, (2) blowout prevention equipment, (3) air compressors--for air drilling, (4) the pipe rack--a horizontal rack for storing thousands of meters of pipe in nine-meter (30-ft) segments, (5) the mud pumps, and (6) engines--as many as three of 500-1000 horsepower. Not shown are the fuel tanks, water tanks, the cooling tower--about 9 m (30 ft) tall and used for cooling the drilling mud during the later stages of drilling, and a cyclone separator--used in air drilling for separating the cuttings from the circulating medium.

In addition to the machinery and mechanical accessories required to drill a well, there are a number of temporary structures which require sufficient space allowance. Among these are the contractor's trailer and the operator's trailer which are used as offices; the logging geologist's trailer; the doghouse, which contains crew lockers, etc; and 1 or 2 out buildings.

Personnel

There are two general categories of workers which keep a drilling rig operating. These are the continuing personnel whose functions require their presence around the clock, and the intermittent personnel whose services are required only at certain stages of the drilling operation.

Among the continuing personnel are the drilling crews of 4 or 5 men each operating in 8-hour shifts, 2 logging geologists, a drilling supervisor each for the contractor and the operator, and, in some instances, a rig superintendent.

Included with the intermittent personnel are the truck drivers who supply diesel fuel, water, mud additives, drill bits, and other equipment; the service personnel who provide such necessary specialized services as cementing, downhole surveys, formation evaluation tests, and the various inspectors concerned with safety and maintaining standards of operation consistent with local, state, and Federal laws. The total number of rig personnel ranges from 17 to 22 and various service personnel from 10 to 15, with a total of 27 to 37 men associated with the rig. The maximum number expected on the site at any given time should be no more than 5 to 10.

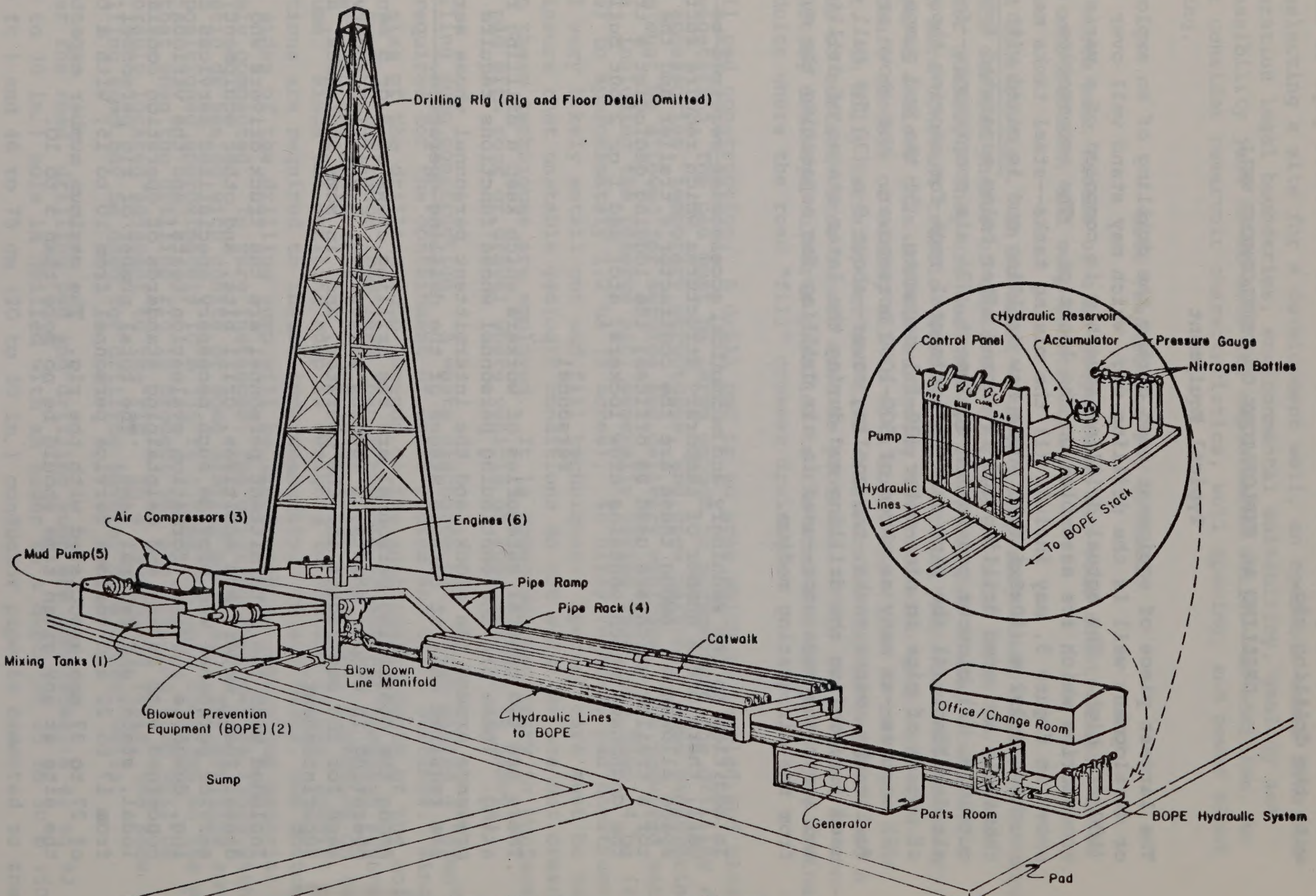


Figure 3: Simplified View of Typical Drilling Site

The Drilling Process

Depending on several variables, but particularly the depth of the hole, the time required to drill a well ranges from 12 to 60 days. The time and expenditures involved may be extended through delays created by mechanical problems, inclement weather, supply shortages, etc.

The method most commonly used for drilling a well is the rotary method. This requires a changeable drill bit, drill pipe, and drilling mud as a circulation medium. At a later stage in the drilling process, air may be utilized, occasionally doubling the time required.

Drilling with mud. The drilling mud is pumped down through the drill pipe, exits through "jets" in the drill bit and travels back up the annular space between the drill pipe and the hole, carrying the cuttings up with it. The mud has several important functions. It cools and lubricates the bit, helps break up the rock, its weight helps keep formation pressures under control, and it brings the cuttings to the surface with a minimum of mixing or settling. This latter function enables the logging geologist to correlate the cuttings with depth, and thus determine the nature of the strata through which the drill bit is passing. The mud also forms a wall cake on the inside of the hole and helps prevent the hole from sloughing in. If high enough temperatures are encountered, drilling mud can "bake", becoming hard, brittle, and useless. By changing over to air drilling (discussed below) this problem can be circumvented.

With the drill bit turning on bottom and the drilling mud in circulation, the drilling team is said to be "making hole." Shallow formations usually drill rapidly and generally surface casing is set and cemented before harder drilling is encountered. Surface casing provides a support for attachment of the blowout preventers and related equipment and maintains the hole through shallow unconsolidated formations.

During routine drilling, the crew must add a joint of drill pipe, or "make a connection," every 10 m (30 ft) or so until the bit is worn out and must be replaced. The length of time between drill bit changes varies greatly with the type of bit and type of formation being penetrated.

Changing the bit is accomplished in an operation called "making a trip," in which the drill pipe is removed from the hole in 20 or 30 m (60 or 90 ft) "stands" which are stacked in a vertical position on the derrick floor. When the drill bit has been changed the trip continues until the bit is on bottom and drilling can be resumed.

Drilling with air. During the drilling, the temperature of the drilling fluid is monitored as it enters and exits from the hole. When temperature differences indicate that the producing zone is being approached and there is no formation water, the decision may be made to change over to air as a circulating medium. At this point a string of production casing is cemented in the hole to the surface. The air compressors and related equipment are brought into use and the drilling process continues much as before.

With air as a circulating medium, the same basic functions are fulfilled as with the mud with a few exceptions. There is effectively no weight to the column of air, so it does not control formation pressures. However, the rock that is being drilled is typically hard and impermeable, so that formation pressure is not normally a problem in such strata. Air as a circulating medium also prevents the producing fractures from being sealed off and rendered incapable of production. Once a productive zone is penetrated and steam vents to the surface, the well is effectively drilled as a controlled producing well.

Drilling with air requires much greater velocities to lift the cuttings than does drilling with viscous mud. Once the steam zone has been penetrated, it is normal to experience return velocities in the range of 2,000 to 3,000 m (6,000 to 10,000 ft) per minute. Sand particles in the air stream are highly erosive and effectively sandblast the drill pipe assembly and the casing. For this reason, the drilling equipment will include an extra-thick metal manifold at the top of the drill pipe called a banjo box to slow down the air flow and a blooie line to divert the rock dust, steam and air to the sump and to muffle the noise. A small amount of silty material may settle onto the area immediately surrounding the drill site, but is not normally of sufficient volume to cause sedimentation of any water bodies.

During air drilling, noise levels, if unchecked, may approach 125 db; however, muffler systems currently in use are designed to reduce the noise to within Federal limits, established as 65 db at a point .8 km (½ mi) from the drill site. The air drilling phase only lasts one to three weeks.

Casing program. Whether the well is produced or not, during drilling the well must be cased to prevent collapse of the hole, maintain zone separation, and allow testing. The casing program that is selected will depend upon the geology and type of geothermal system. For example, dry steam is produced from hard, fractured rock at the Geysers geothermal field, and superheated water or brine is produced from loosely consolidated sediments in the Salton Sea area of California.

The casing program of an exploratory or production well will generally consist of the following for any area: conductor set to 15 m (50 ft), surface casing to ± 60 m (200 ft), primarily to provide an anchor for blowout equipment, and a string or production casing. Sometimes an intermediate casing is used between the surface casing and the string or production casing to protect interlying zones. For an area such as The Geysers, the final portion of the well is open hole below the intermediate casing (fig. 4). For areas such as the Salton Sea, slotted liner is required in the lower portion to control sand flow.

Casing programs for wildcat wells will vary somewhere between these two extremes depending on the type of geothermal system (hot water or dry steam), the character of the producing zone (hard rock or sediment), and other factors.

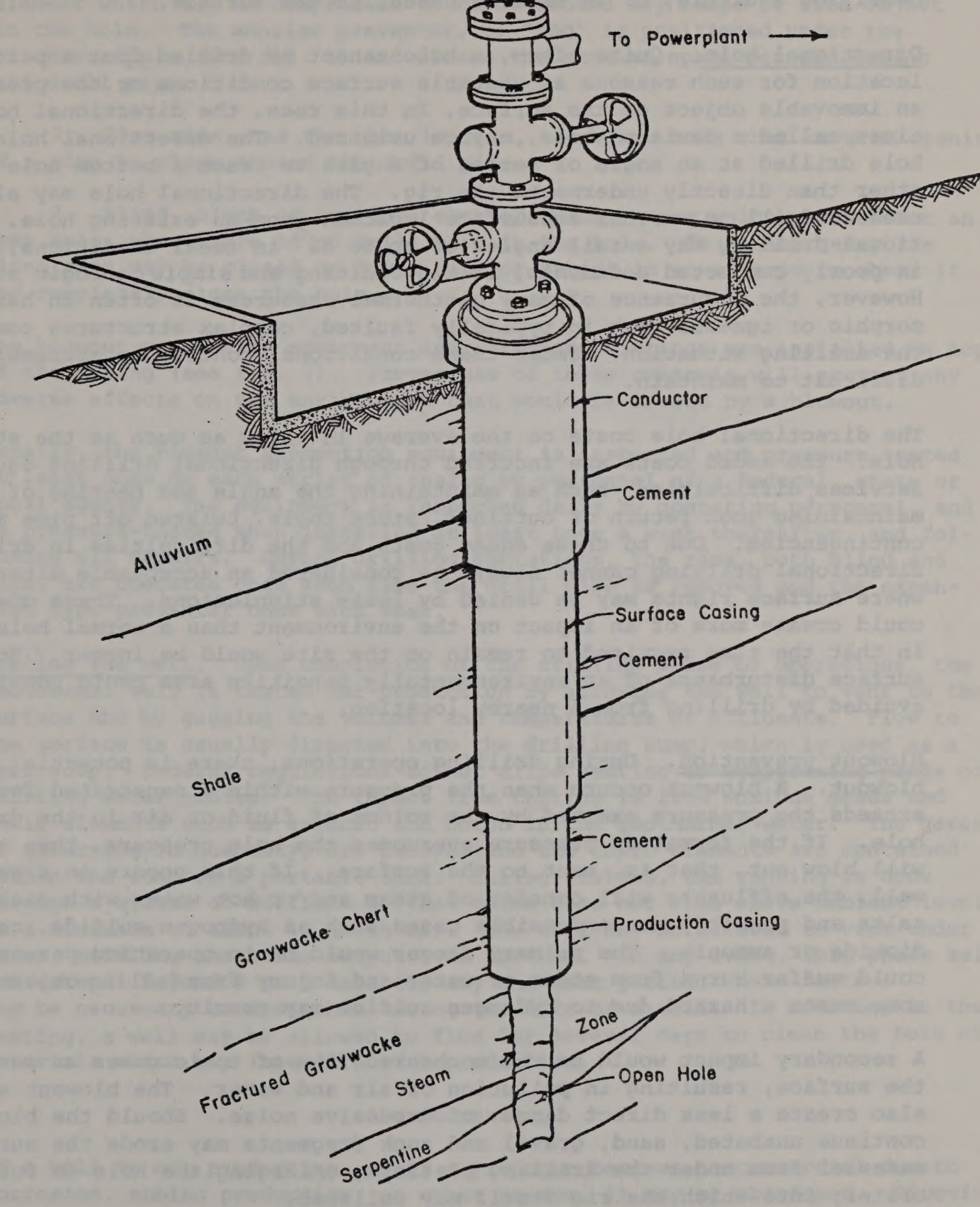


Figure 4: Typical Casing Program For a Production Well

If the completion is done properly, there is no impact on the environment. If done improperly, geothermal fluids could leak from the producing zone to overlying aquifers, or in extreme cases, to the surface.

Directional hole. Quite often, a hole cannot be drilled from a particular location for such reasons as unstable surface conditions or the presence of an immovable object on the surface. In this case, the directional hole, sometimes called a deviated hole, may be utilized. The directional hole is a hole drilled at an angle or series of angles to reach a bottom hole location other than directly underneath the rig. The directional hole may also be used to drill to another subsurface location from an existing hole. Directional drilling may entail angles of up to 85° in ideal conditions, that is, in poorly compacted sediments, little faulting and simple geologic structures, However, the occurrence of many geothermal resources is often in hard metamorphic or igneous rock in typically faulted, complex structures complicating the drilling situation. Under these conditions, control is extremely difficult to maintain.

The directional hole costs on the average 1½ times as much as the straight hole. The added costs are incurred through directional drilling equipment, services, difficulties such as maintaining the angle and bearing of the hole, maintaining good return of cuttings, stuck tools, twisted off pipe and other contingencies. Due to these added costs and the difficulties in drilling, directional drilling cannot always be considered an acceptable alternative where surface rights may be denied by lease stipulations. These operations could create more of an impact on the environment than a normal hole would in that the time required to remain on the site would be longer. However, surface disturbance of an environmentally sensitive area could possibly be avoided by drilling from a nearby location.

Blowout prevention. During drilling operations, there is potential for a blowout. A blowout occurs when the pressure within a penetrated formation exceeds the pressure exerted by the column of fluid or air in the drilled hole. If the formation pressure overcomes the hole pressure, then the well will blow out, that is, vent to the surface. If this occurs in a geothermal well, the effluents will consist of steam and/or hot water with dissolved salts and possibly noncondensible gases such as hydrogen sulfide, carbon dioxide or ammonia. The primary danger would be to operating personnel, who could suffer burns from steam or water and injury from falling objects. In some cases a hazard due to hydrogen sulfide may result.

A secondary impact would be the unchecked flow of toxic gases or water to the surface, resulting in pollution of air and water. The blowout would also create a less direct danger of excessive noise. Should the blowout continue unabated, sand, gravel and rock fragments may erode the surface material from under the drilling platform, enlarging the hole to form a crater, into which the rig itself may collapse.

Controls must be installed on the casing to prevent such an occurrence. Blowout prevention equipment comes in various forms, and varying grades of equipment are required depending upon the area being drilled, depth of the well, expected pressures, and past drilling experience in the area. The equipment consists essentially of one or more of the following three items:

1. Annular preventer - a device that contains a reinforced flexible element which may be compressed to close around any shape or size object in the hole. The annular preventer, or "bag," is positioned under the pitcher nipple (see fig. 5) and closes the annular space between casing and drill pipe.

2. Pipe rams - as the name implies, these are rams that have an opening of a size to close around the drill pipe.

3. Blind, blank or complete shut-off rams - rams which are used on an open hole, when there is no drill pipe in the hole. In an emergency the blind rams may be closed on drill pipe or tubing in an attempt to shear it and completely close the hole.

The blowout prevention equipment and attendant fittings are installed on top of the casing (see fig. 5). Proper use of these controls will prevent any adverse effects on the environment that would be caused by a blowout.

Usually, the blowout prevention equipment is inspected and pressure tested at least once on each string of casing by personnel of a Federal, state or local agency. The equipment is inspected daily by operating personnel, and is pressure-tested when installed at least once a week thereafter, and following all repairs. During drilling operations, the rams, both blind and pipe, are operated once each time the drill pipe is removed and the expansion type preventer once each week.

Testing the well. Upon completion of the drilling phase of operations, the geothermal well is tested for production by allowing the well to vent to the surface and by gauging the volumes and temperatures of effluents. Flow to the surface is usually directed into the drilling sump, which is used as a test sump. Federal regulations do not allow venting to evaporating ponds or existing water bodies. The impact from testing is from noxious gases and toxic elements such as arsenic and boron in the geothermal water. The gases, if occurring in quantity, are removed and the toxic elements are contained within the sump or a portable tank. During testing, the venting is done through a system of mufflers so that noise does not rise above ambient levels at a distance of about .8 km (½ mi). The well may be allowed to vent under water, muffling the noise output even further. In any event, this phase seldom extends beyond 2 or 3 days for any one test period. More tests may be necessary or desirable during the life of a well. In addition to the testing, a well may be allowed to flow for several days to clean the hole of any materials which may interfere with production.

Abandonment

If a well is not productive, or if a producer becomes noncommercial due to corrosion, ebbing production, or other causes, it may be abandoned. Plugging

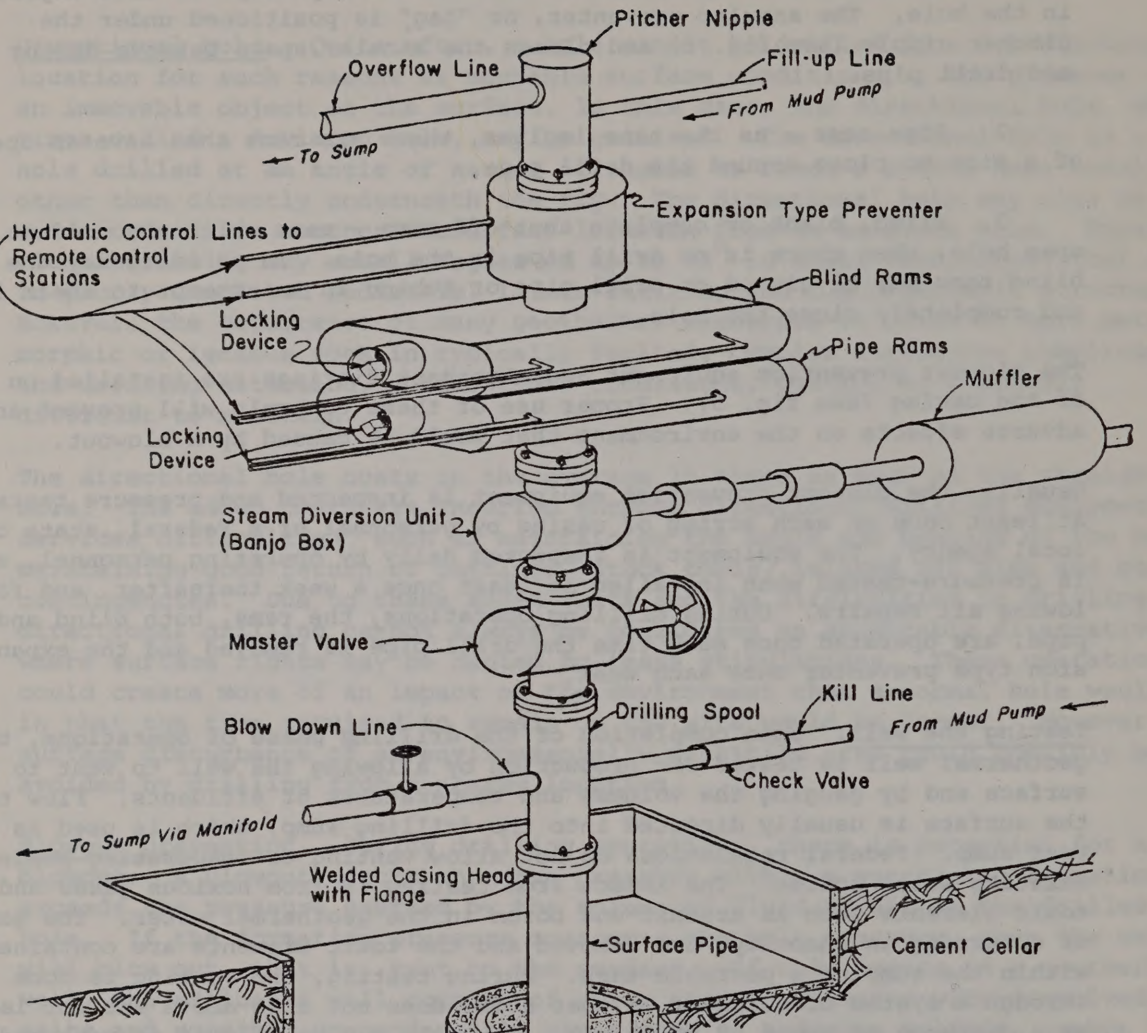


Figure 5: Typical Blowout Prevention Equipment

and abandonment of a well must satisfy Federal, state, and local law. In general, the laws are similar and seek to protect the environment. Requirements for abandonment vary upon the type of hole drilled, depth, formations encountered, and other factors (fig. 6).

Generally, the simplest requirements are for shallow (less than 150 m or 500 ft) temperature gradient holes. These wells are filled with drilling mud to a depth of 3 m (10 ft) and with a cement plug from 3 m (10 ft) to the surface or with cement from total depth to surface, depending on the character of fluids encountered. Observation holes are deeper (around 500 m or 1500 ft) and require more plugs.

As a rule, exploratory or production wells are even deeper and more complex and require correspondingly more plugs. The number of plugs required generally increases with the depth, the complexity of the regional geology, the complexity of the well, the material left in the hole such as twisted-off drill pipe, and other conditions. The intent is to prevent the movement of fluids in the well bore so that there is no movement between zones or flow to the surface. Portions of the well bore not filled with cement are filled with drilling mud. Once all plugs have been set, the casing is cut off at least 2 m (6 ft) below the ground surface and capped by welding on a steel plate. Cellars, pads and all other structures are removed and the surface area returned to the original grade. All remaining refuse must be removed from the area and the site reclaimed or revegetated to the specifications of the surface managing agency.

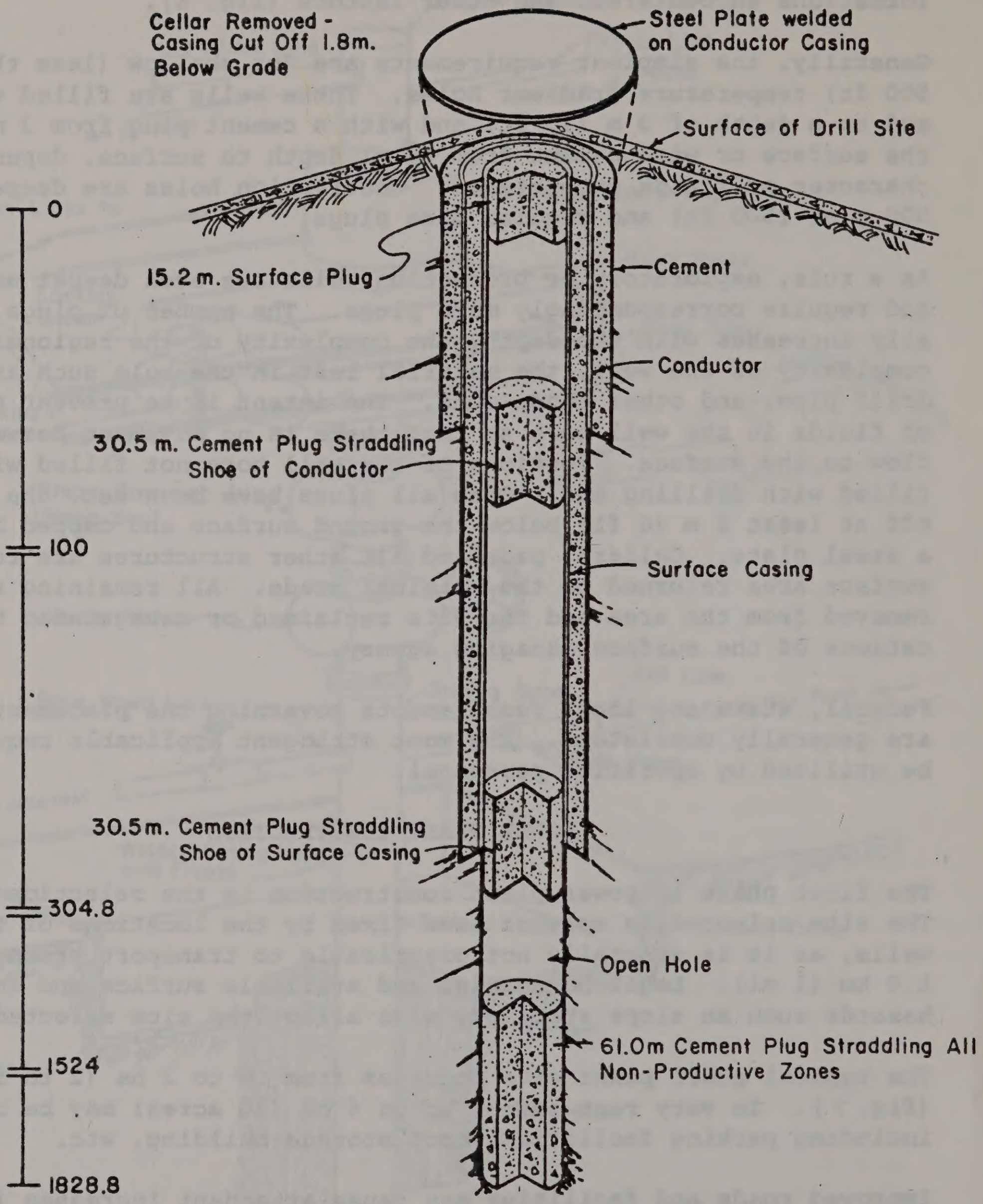
Federal, state and local requirements governing the placement of cement plugs are generally consistent. The most stringent applicable requirements must be utilized by operating personnel.

POWER PLANT CONSTRUCTION

The first phase in power plant construction is the selection of a site. The site selected is more or less fixed by the locations of the geothermal wells, as it is generally not practicable to transport steam much more than 1.6 km (1 mi). Legal boundaries and available surface and engineering hazards such as slope stability also affect the site selected.

The typical power plant site occupies from .8 to 2 ha (2 to 5 acres) (fig. 7). In very rare cases, up to 4 ha (10 acres) may be utilized, including parking facilities, tool storage building, etc.

Improved roads and facilities may cause attendant increases in runoff and erosion. After the power plant is constructed, elevated steam lines are run from each well, 1 to 2 meters above the ground, creating a surface network of pipes. The pipes must be able to expand and contract, and are therefore generally not placed underground for great distances. Pipes about 50 cm (20 in.) in diameter are connected at intervals with expansion loops several meters high. The size of the network will depend on the number of wells required to power the steam turbine. Individual wells in The Geysers average about seven megawatts; this means that a 1,000 Mw power plant would


Cellar Removed - Casing Cut Off 1.8m. Below Grade
Steel Plate welded on Conductor Casing
Surface of Drill Site
0
15.2 m. Surface Plug
Cement
Conductor
30.5 m. Cement Plug Straddling Shoe of Conductor
100
Surface Casing
Depth in Meters
30.5m. Cement Plug Straddling Shoe of Surface Casing
304.8
Open Hole
61.0m Cement Plug Straddling All Non-Productive Zones
1524
1828.8

Note: All portions of the casing or hole not filled with cement are filled with heavy drilling mud.

Figure 6: Typical Abandonment of Exploratory Well

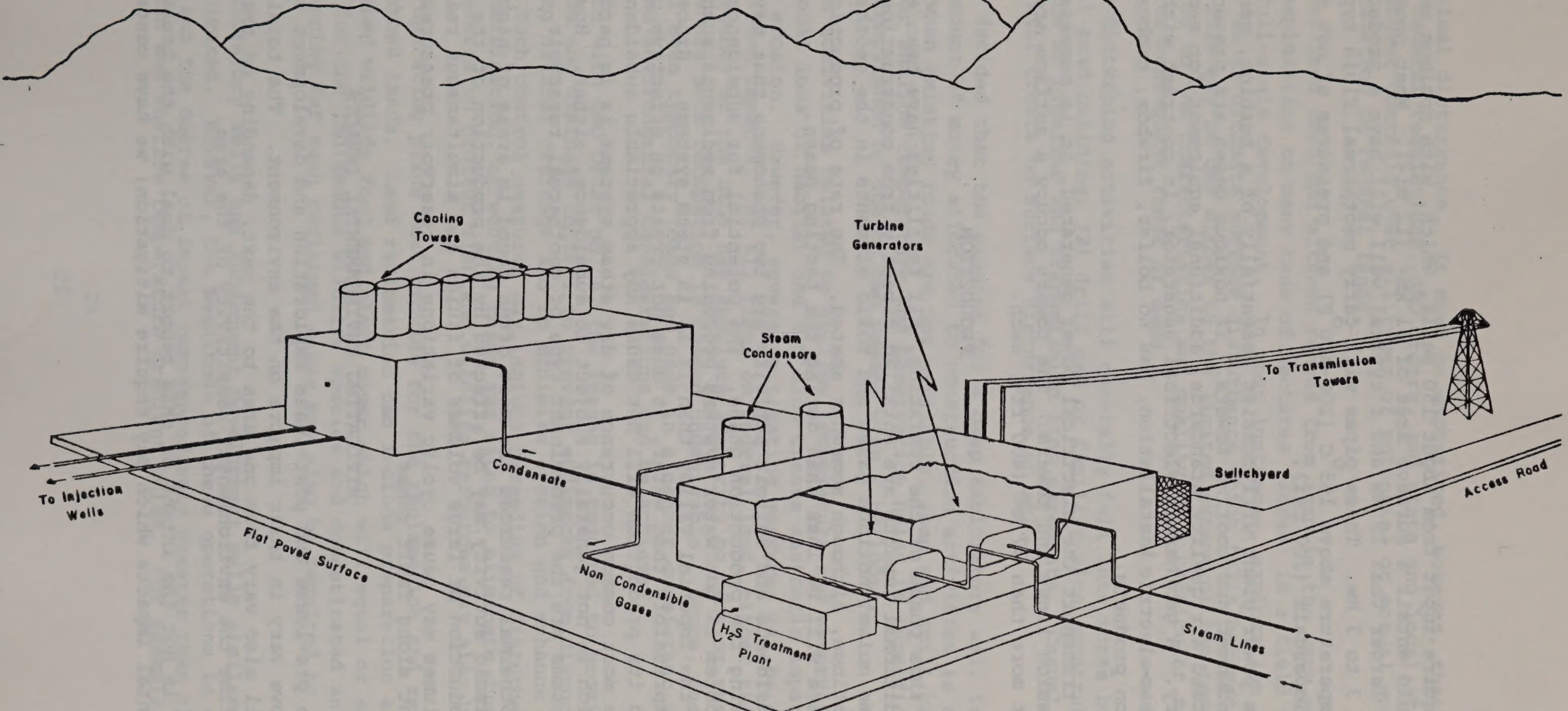


Figure 7: Simplified View of Typical Power Plant Site

require input from about 150 wells, which, with optimum well spacing, would entail a surface area of 31 km^2 (12 mi^2). Most power plants are no larger than 55 Mw and a typical well will have a productive capability of 3 to 5 Mw. These pipes will carry geothermal fluid typically at a temperature above 165°C (200-400°F) and pressures of not more than 1380 kilopascals (200 psi).

The power plant will consist essentially of a turbine, generator, steam condenser, and cooling towers. If noxious gases are present which might exceed air quality standards, additional equipment for removal is necessary. A geothermal electrical generator, in contrast with a conventional steam-electric installation, has no boiler, firebox, combustion, or combustion products.

To transport the electrical power generated, it is necessary to use transmission lines and towers. The towers occupy a surface area of probably not more than 37 m^2 (400 ft^2) each.

PRODUCTION

By this phase of the operation, all facilities have been erected and no additional impacts are entailed directly from construction activities. Some noise, noxious gases and toxic elements in the geothermal waters will continue, although somewhat abated. The rate of production of each of these will be less than during the testing phase.

Subsidence and seismic activity are two phenomena that may be accentuated during the production phase. The potential for subsidence is a greater problem in hot water systems producing from sediments such as those found in the Imperial Valley than it is in steam systems. Since steam is more compressible than water, it does not create an effective pore pressure, and its production will not cause any appreciable subsidence. Furthermore, the most common occurrence of dry steam systems is in hard, competent rock which is not generally subject to subsidence, either. However, hot water systems are the predominant type of geothermal reservoir.

Geothermal resources are most often found in areas of high seismic activity. Seismic activity may be affected by the production of the geothermal resource. Production of large volumes of fluids and simultaneous reinjection of similar volumes may cause cyclic variations in reservoir pressures with possible movement along fault zones.

MITIGATING ENVIRONMENTAL IMPACTS

The pre-lease and post-lease exploration and development activities described above vary in their impacts on the environment. The total environmental impact will also vary from one area to the next, depending on the many factors which define the environmental sensitivity of the area.

It is not the intent of this report to deal with the broad range of environmental impacts which may require mitigation; we have concentrated instead on actual physical disturbance. It must be emphasized, however, that a variety of Federal regulations, GRO Orders, and state and local statutes invoke stringent controls over all types of potential or actual environmental degradation on Federal lands.

The amount of land used and altered ranges from zero in the very earliest stages of exploration to many tens of hectares (acres) in a field which has undergone full-scale development. In most instances, exploration activities will result in an ultimate surface disturbance which falls between these two extremes. This may be due either to the limited extent of the resource in a given area or to the characteristics and quality of a particular reservoir fluid and its consequent range of uses.

The surface disturbing activities will generally fall into three broad categories: (1) road building, (2) drill pad or facility site construction and, (3) clearance of pipeline and transmission line easements. Casual use activities will create no surface disturbance at all.

Until it is decided that the expense for a deep exploratory well is justified, the amount of money allocated to construction activities is nominal. Therefore, when existing roads are not available, road and drill pad construction for shallow temperature and observation holes is superficial and is often accomplished by one or two passes with a bulldozer.

Construction activities related to shallow temperature and observation holes result in local loss of habitat and can also create aesthetic impacts or accelerated erosion. However, several mitigating measures may be employed to minimize such impacts. At all times on Federal land, either the surface management agency or the USGS has absolute authority to deny or restrict occupation where such occupation is deemed undesirable. Hence, the optimum placement of even temporary roads and pads in a manner consistent with sound aesthetic and environmental considerations can be achieved.

In accordance with GRO Order No. 4, the lessee is required to provide adequate erosion and drainage control to prevent sediments from disturbed sites from entering natural drainage and to minimize erosion and enhance slope stability. Such control measures may include reseeding of disturbed soils, chemical stabilization, or wetting roads and sites to eliminate dust. Specific measures to protect fish and wildlife resources may also be required.

Permits and operating plans must provide for the reclamation and revegetation of all disturbed lands. Land reclamation can include preparation and seeding with prescribed wildlife food and plant cover which will equal or enhance the food values for the indigenous wildlife species and domesticated animals. Temporary fencing for such reclaimed areas may also be required to facilitate restoration.

For deep exploratory wells and subsequent development wells similar impacts can be anticipated. However, the magnitude of these operations is generally much larger and the degree of impact correspondingly greater than that caused by observation and shallow temperature gradient holes. For example, roads are wider and drill pads are appreciably larger, resulting in a greater loss of habitat. If commercial production is obtained, the impacts created by each subsequent development well are essentially cumulative and much of the surface disturbance is relatively permanent (given an expected minimum lifespan of 30 years). Nevertheless, the mitigating measures described for shallow temperature and stratigraphic holes are equally applicable here.

Where development results in the construction of a power plant or other facilities, there will be a similar long-term loss of habitat. However, efforts to reduce the visual impacts and ensure slope or ground stability are employed. In addition to the mitigating measures described above, the design and construction of facilities are such that all facilities blend into the natural environmental setting of the area by appropriate use of landscaping, vegetation, compatible color schemes, and minimum profiles. Native plants or other compatible vegetation may be used for landscaping, soil stabilization, and revegetation.

Vegetation is removed as necessary for pipeline and transmission line easements to provide a bare ground buffer zone. Although requirements and practices may vary from state to state, easements up to 3 m (10 ft) on each side of pipelines or transmission lines can be expected. Pipelines themselves will not normally present a hazard to wildlife. They are insulated and generally elevated a meter or so (two to several feet) above the ground and are also designed with periodic expansion loops or U-shaped expansion joints. Pipelines can therefore be aligned and designed to minimize interference with transitory and indigenous wildlife. To reduce the visual impact of a pipeline, it may be camouflaged to blend in with the natural environment.

ALTERNATIVE APPLICATIONS OF GEOTHERMAL ENERGY

On the basis of our current technology, highly favorable geologic and reservoir conditions must exist for power generation from geothermal resources to be practical. The most important of these conditions are as follows: (1) reservoir temperatures must be high, (2) a medium, such as water or steam, is needed for delivering the heat to the surface, (3) the reservoir must be sufficiently permeable to adequately transmit fluids and thereby ensure sustained heat flow rates at the surface, and (4) since the cost of a power plant is generally amortized over a period of 30 years, the reservoir must be sufficiently extensive or be recharged at such a rate as to ensure commercial production over a prolonged period of time. Even if these four conditions occur together, a fifth factor could render the reservoir uncommercial under present technology. If the produced fluid is highly corrosive or otherwise incompatible with typical production or power generation equipment, as is the case in part of Imperial Valley, either new technology must be made available or the above first four reservoir conditions must be exceptionally favorable in order to offset the increased production and development costs incurred in dealing with the problem.

With present technology, temperatures greater than 160°C (320°F) at the surface are normally required for operation of a binary power plant. This is a plant in which the produced heat is transferred to a low boiling point fluid (such as freon or isobutane) which is then used as the working fluid in a closed cycle system. In the Soviet Union, geothermal fluids with temperatures as low as 81.5°C have been used to generate electricity. However, their 750 kW binary power plant operates at a cost per kilowatt 2 to 8 times higher than that for power plants utilizing higher temperature fluids. Temperatures greater than 180°C (355°F) are required for operation of a conventional geothermal power plant. These temperatures are based on sustained flow rates of 9.1 kg (20 lbs) per hour per kilowatt.

The vast majority of those geothermal systems presently known to exist will not meet the above criteria. Their expected temperatures range from 50°C (120°F) to 160°C (320°F) and their fluid and reservoir characteristics are largely unknown. However, despite their anticipated lower available heat energy, such systems can significantly supplement the total energy picture if used for non-electrical applications. (See Table 3 for the temperature ranges for various applications.)

Table 1 is a representative, although not necessarily complete, listing of present low temperature geothermal applications in the United States. This list, however, only scratches the surface of the potential extent of low temperature geothermal utilization in the U.S. Table 2 summarizes some of the innovative uses to which geothermal heat has been applied in other parts of the world.

One of the most direct and potentially one of the most widespread applications of lower temperature geothermal resources is for space heating and cooling. For example, the Oregon Institute of Technology began utilizing geothermal hot water in 1964 for heating the buildings and facilities on campus. In the previous three years the campus averaged $94,000 a year in heating costs. Using hot water for heating, the Institute's annual operating cost today (1975) is $12,600. This represents a savings of $81,400, but more importantly, it represents a considerable decrease in demand on other diminishing energy resources. Artificial heating and cooling of houses and businesses requires large expenditures of energy, which is presently supplied primarily by fossil fuels. Fossil fuels are costly, reserves are being depleted and their use further pollutes our environment. Therefore, increased reliance on geothermal heat will play a significant and increasing role in the future energy policies of the United States.

SUMMARY

In the preceding discussion we have attempted to present a realistic picture of the typical sequence of events likely to occur in searching for, and ultimately developing, a geothermal resource. No one geological or geophysical survey, or suite of surveys provides a diagnostic measure of a geothermal resource. An operator seeks to reduce his financial risk for a potential project by the acquisition of subsurface information, but must limit the cost of such information to well below the speculative returns. Each successive step is, therefore, strongly influenced by the results of steps which have preceded it. It cannot be overemphasized that of all the leased land on which exploration will be initiated, only those relatively few leases having the greatest potential are likely to undergo total development, and exploration will leave no lasting environmental effects on the majority of those leases which do not reach the development stage.

It should also be emphasized that it has not been our intent in this paper to evaluate the entire range of potential effects which geothermal exploration and development could have under varying circumstances. We hope that the discussions of the relative impacts of each action in terms of actual physical disturbance of the surface help the reader to make meaningful analogies to a wide range of environments which vary in flora, fauna, climate, topography, and public sensitivity.

Applications of Geothermal Energy in the United States

Applications Now in Effect

ALASKA

1. Swimming pools and bathhouses
2. Greenhouses
3. Limited space heating

CALIFORNIA

1. Power generation
2. Space heating
3. Heating water for domestic use
4. Greenhouses
5. Spas and recreation
6. Lumber mill drying kilns

IDAHO

1. Space heating
2. Domestic hot water
3. Greenhouses
4. Swimming pools, resort use
5. Fish propagation (mainly catfish)
6. Irrigation
7. Animal husbandry (warm water watering during winter months)
8. Forest campgrounds

NEVADA

1. Source of water for domestic use
2. Space heating
3. Safe heat source for processing explosives
4. Spas and recreation
5. Greenhouses

OREGON

1. Space heating
2. Heating water for domestic use
3. Pasteurization
4. Industrial cleaning
5. Refrigeration
6. Coils under pavement to prevent accumulation of ice and snow
7. Greenhouses
8. Tree seedling nurseries

POSSIBLE FUTURE APPLICATIONS

1. Sugar processing
2. Fermentation processes
3. Freeze drying of food
4. Production of heavy H_2O
5. Mineral extraction from brines
6. Production of alumina from bauxite
7. Gasification of coal and other carbonaceous
8. Textile processing
9. Products of fermentations: Ethyl alcohol, butanol acetone, citric acid, etc.

TABLE 1

Applications of Geothermal Energy
Outside the United States

HUNGARY

1. Greenhouses
2. Animal Husbandry
3. Space Heating
4. Crop Drying

ICELAND

1. Space heating on a large scale (40% of population)
2. Hot houses for flowers and vegetables
3. Industrial utilization
4. Power generation
5. Drying of seaweeds
6. Curing cement building slabs
7. Mining of diatomaceous earth
8. Fish husbandry (salmon)

ITALY

1. Power generation
2. Chemical production
3. Ore Processing

JAPAN

1. Space heating
2. Melting road snow
3. Sewage heat treating
4. Livestock barn heating
5. Egg hatching and poultry
6. Power generation
7. Tropical animal husbandry
8. Tropical and food fish husbandry, eels
9. Greenhouses
10. Sapling growing
11. Soil disinfecting
12. Heating irrigation water
13. Cooking
14. Bathing
15. Heating swimming pools and fire fighting water
16. Salt making or desalting sea water
17. Tropical gardens

JAPAN (Continued)

18. Food drying, processing
19. Mineral water and medicinal
20. Rice processing
21. Extraction of gases
22. Production of sulfuric acid
23. Brewing and distillation
24. Raising alligators and crocodiles
25. Sinter extraction (alum)

MEXICO

1. Power generation

NEW ZEALAND

1. Process heat for newsprint, pump and lumber mills
2. Space heating
3. Power generation
4. Space cooling by lithium bromide absorption unit powered with geothermal heat
5. Biodegradation of wastes from pigsties
6. Washing and drying of wool
7. Soil and bulb sterilization
8. Tree seedling nurseries
9. Cooking and sterilizing garbage feed
10. Alfalfa drying

USSR

1. Domestic hot water
2. Space heating
3. Greenhouses
4. Soil Heating (permafrost)
5. Industrial uses
6. Mining uses
7. Dairy farming
8. Power generation (experimental)
9. Iodine recovery

TABLE 2

TEMPERATURES REQUIRED FOR VARIOUS GEOTHERMAL APPLICATIONS *

°C	
200	
190	
	Evaporation of Highly Concentrated Solutions
180	Refrigeration by Ammonia Absorption
	Digestion in Paper Pulp
170	Heavy Water via H_2S Processing
	Drying of Diatomaceous Earth
160	Drying of Fish Meal
	Drying of Timber
150	Alumina Via Bayers Process
140	Drying Farm Products at High Rates
	Canning of Food
130	Evaporation in Sugar Refining
	Extraction of Salts by Evaporation and Crystallization
120	Fresh Water by Distillation. Most Multiple Effect Evaporations,
	Concentration of Saline Solutions. Refrigeration by Medium
110	Temperatures
	Drying and Curing of Light Aggregate Cement Slabs
100	Drying of Organic Materials, Seaweeds, Grass, Vegetables, etc.
	Washing and Drying of Wool
90	Drying of Stock Fish
	De-Icing Operations
80	Space Heating
	Greenhouses by Space Heating
70	Pasteurization (harmful bacteria killed at 74.4°C or 166°F)
	Refrigeration by Low Temperatures
60	Animal Husbandry
	Greenhouses by Combined Space and Hotbed Heating
50	Mushroom Growing
	Balneological Baths
40	Soil Warming
30	Swimming Pools, Biodegrading, Fermentating
	Warm Water for Year-around Mining in Cold Climates. De-Icing
20	Hatching of Fish. Fish Farming.

Saturated Steam

Water

Temperature range of conventional power production

Present expected temperature range for binary power plants

*adapted from Geothermal Energy for Process Use by Baldur Lindal in Study Guide from International Conference on Geothermal Energy for Industrial, Agricultural and Commercial-Residential Uses. Klamath Falls, Oregon, October 7-9, 1974.

TABLE 3

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Credits for Photos

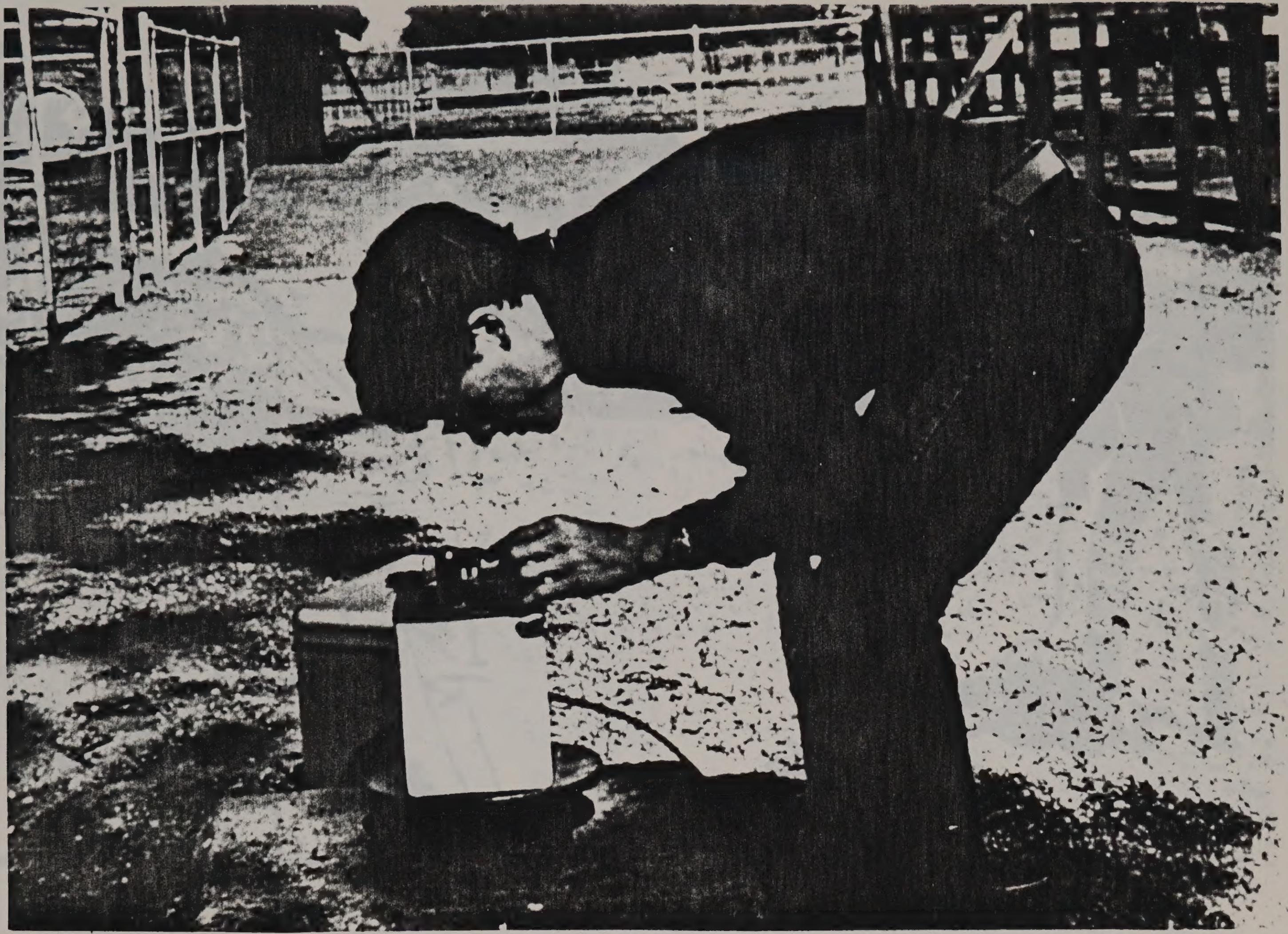
Plates 1, 2, 4, 5, 6, 7, 8, 9, 13, and 14: U. S. Geological Survey

Plate 3: Tsvi Meidav, Geonomics

Plates 10, 11, and 12: Pacific Gas and Electric Company

Water sampling - Above, water is tested for pH value. Below, specific conductivity is measured to determine amount of dissolved solids.

Plate 1

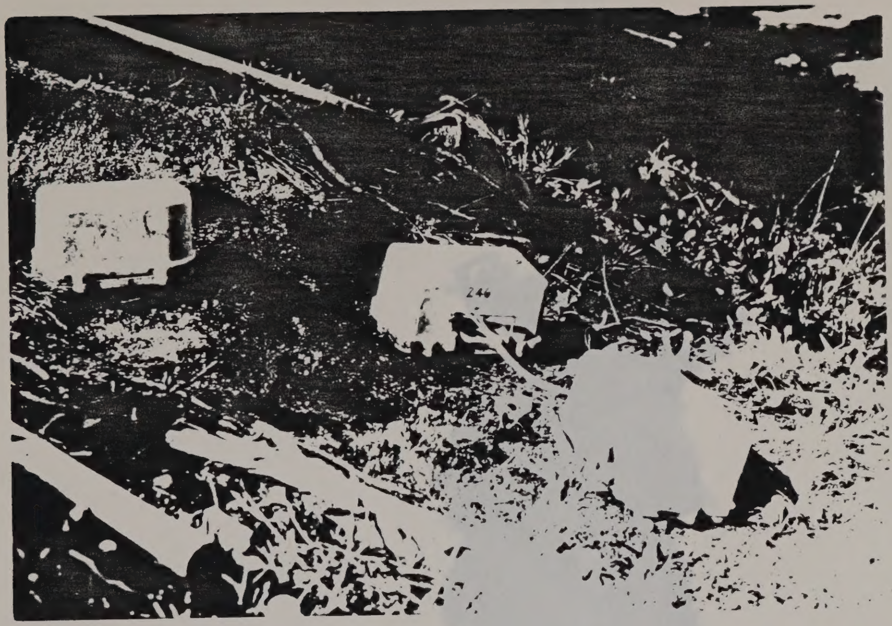


Gravity survey - Portable gravimeter measures variations in gravity values.

Plate 2

Magnetic survey - Variations in magnetism help define geothermal areas. Similar equipment is used for resistivity and magnetotelluric surveys. (Photo - Tsvi Meidav, Geonomics)

Plate 3

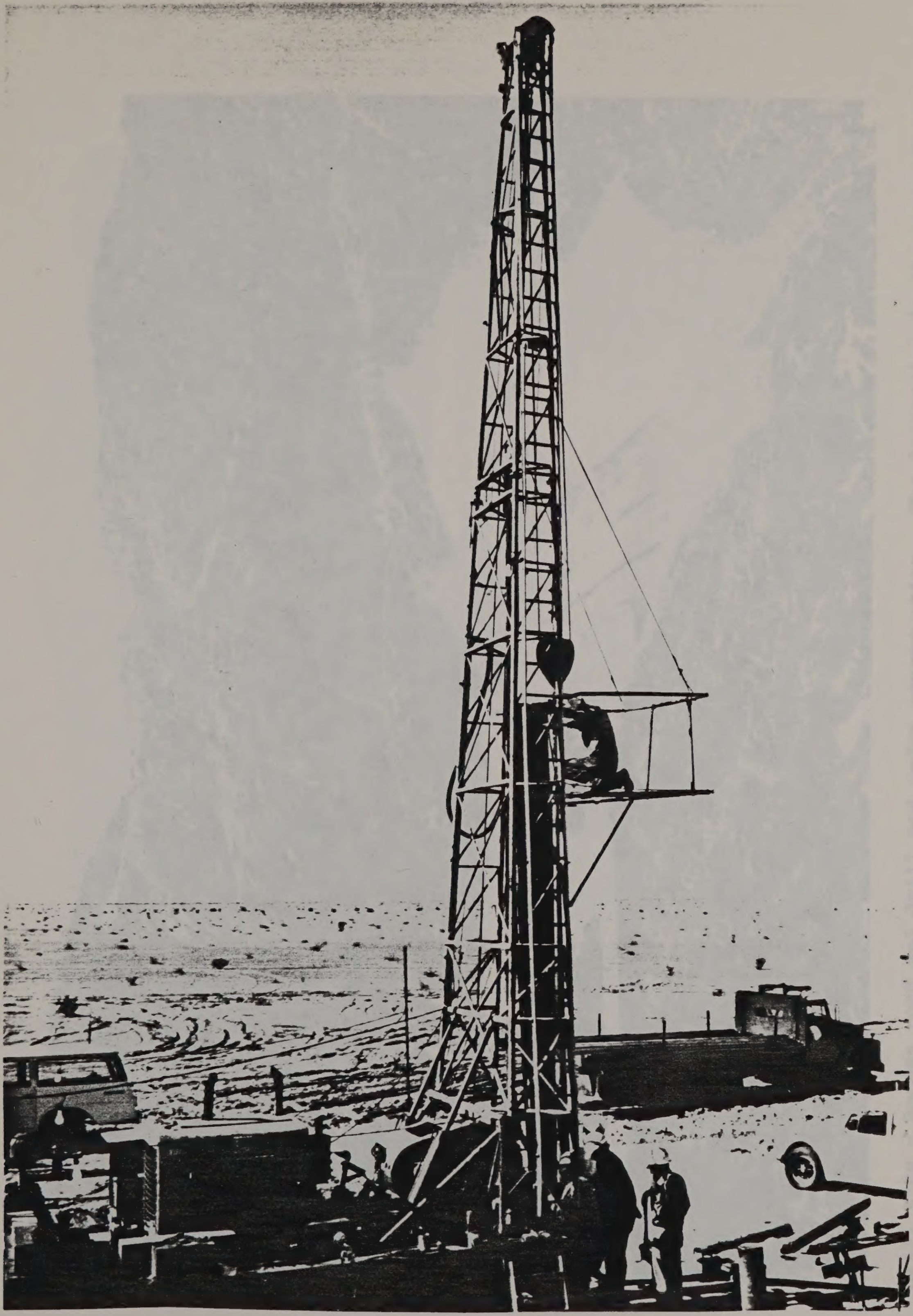


Passive seismic studies - Above, geophones are planted just below the surface to detect microearthquakes. Below, technician connects tape recorder to seismic monitoring equipment.

Plate 4

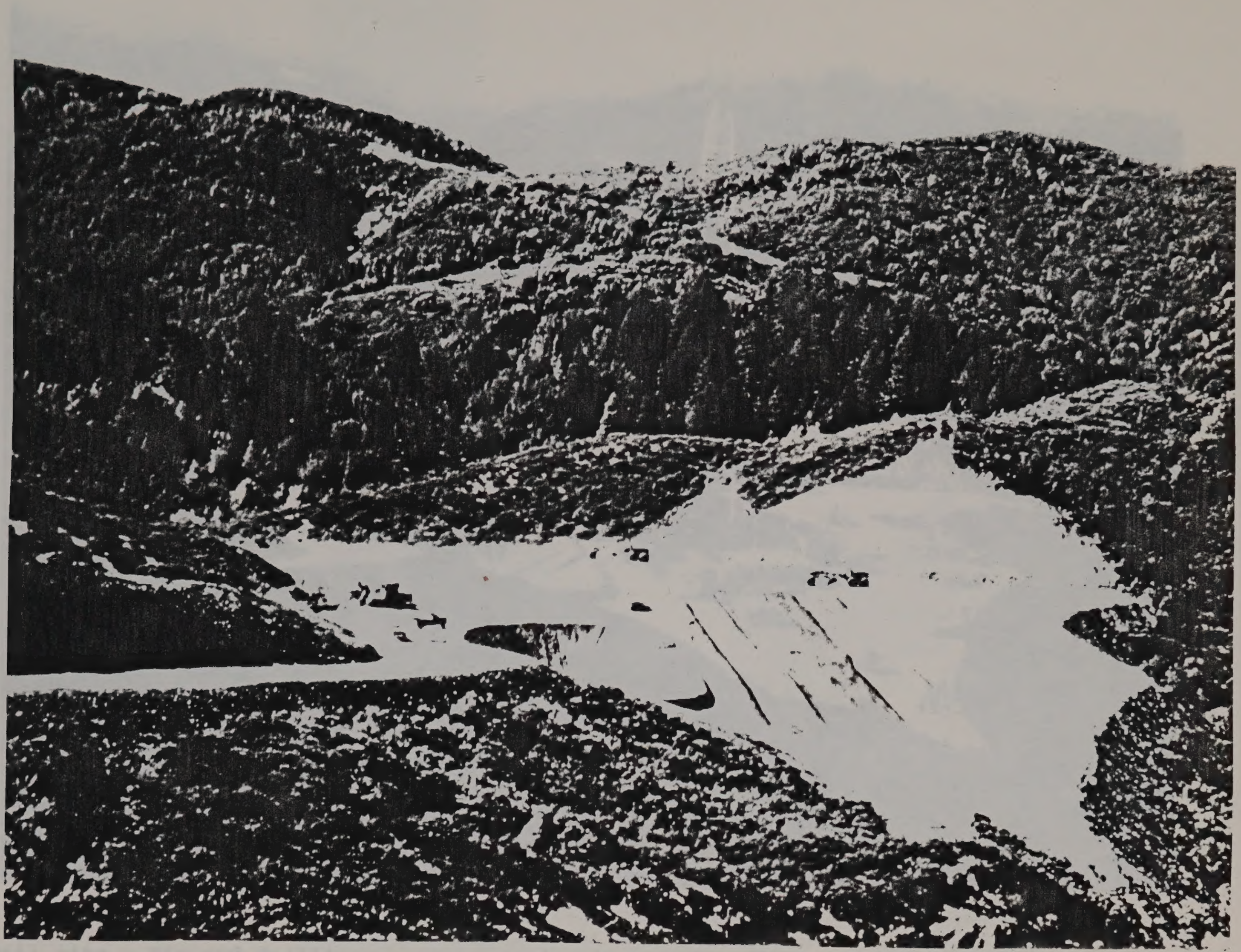
Active seismic study (explosive method) - An explosive charge is detonated in a shot hole, and subsequent vibrations are recorded.

Plate 5



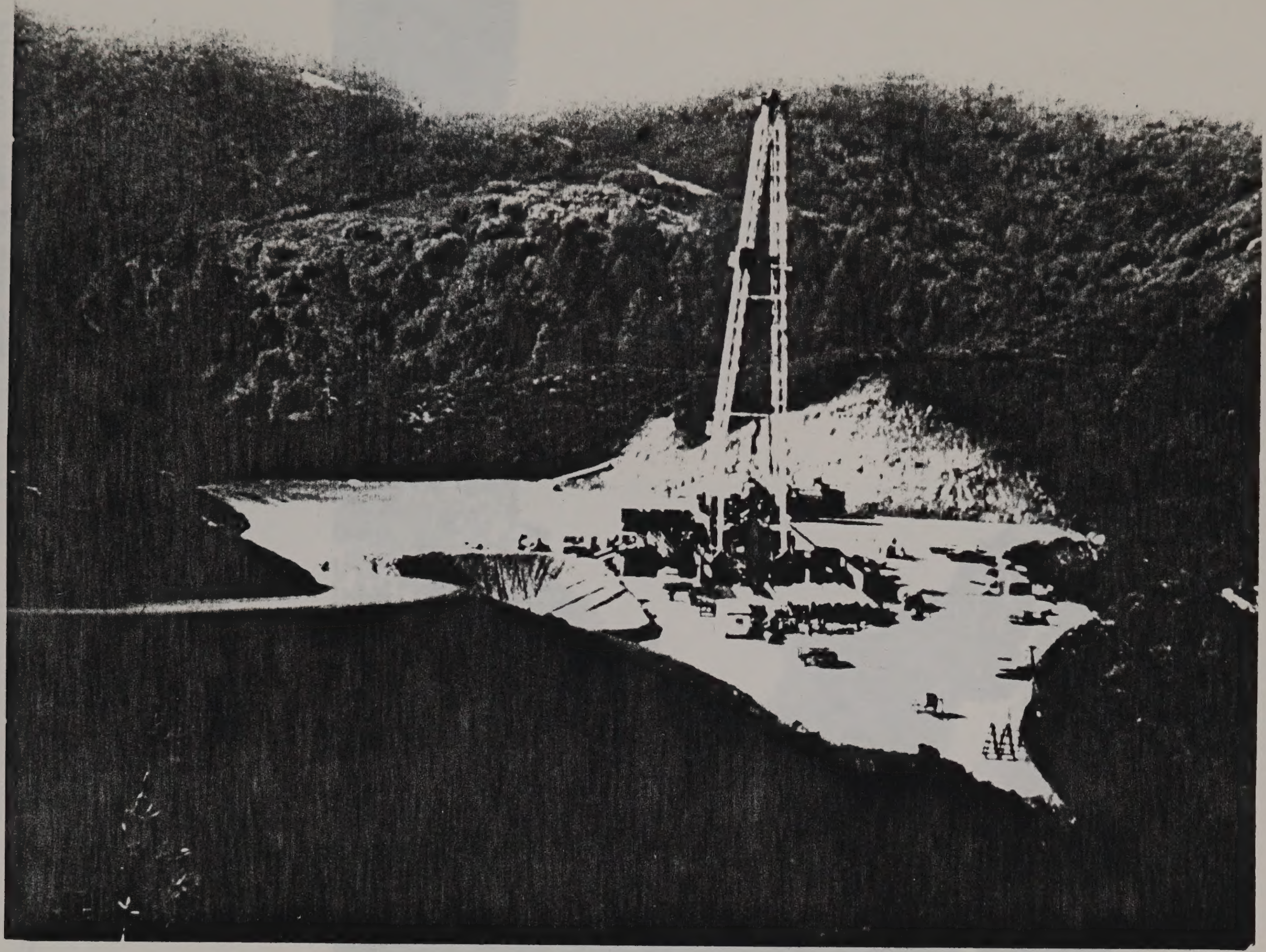
Shallow temperature gradient hole - A typical truck-mounted rig for drilling shallow temperature gradient holes. Rigs for drilling observation holes are similar.

Plate 6



Drill site - Access road and drill pad under construction. The depression is the sump where excess drilling mud and drill cuttings are stored.

Plate 7

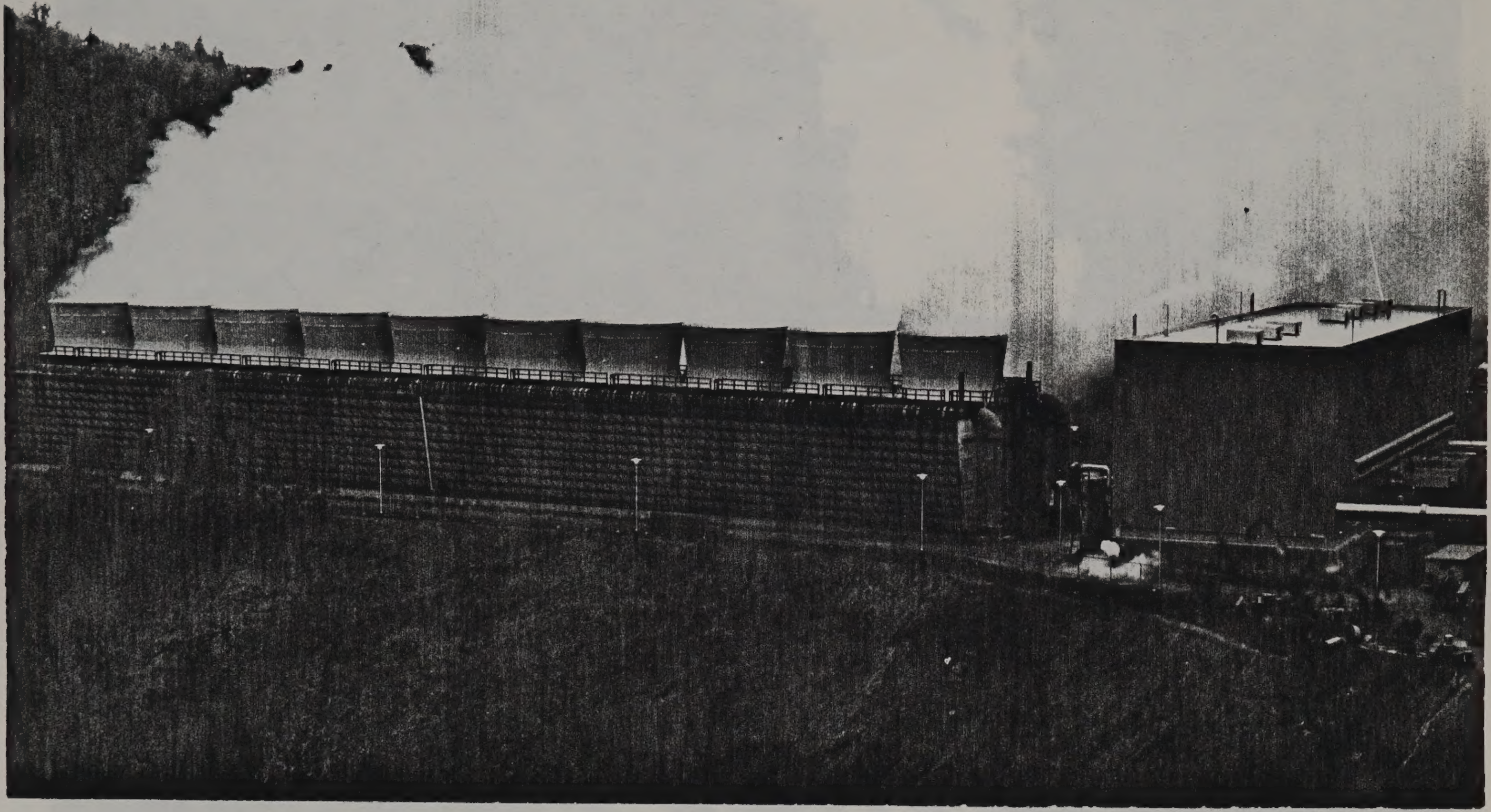


Drill site - Rig and drilling accessories in place and ready for drilling.

Plate 8

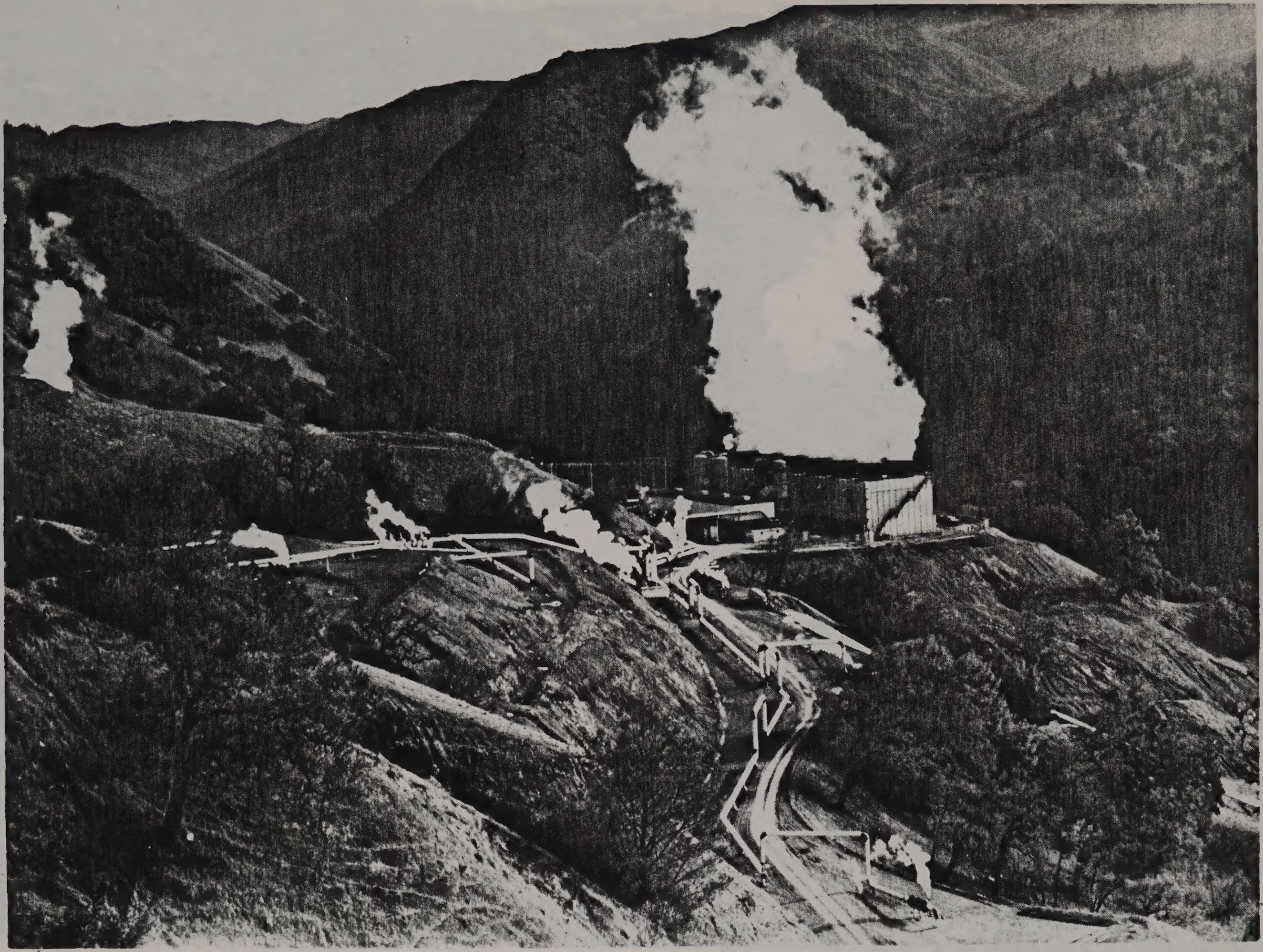
Testing - the steam well is being tested for production capability by blowing down to the sump.

Plate 9

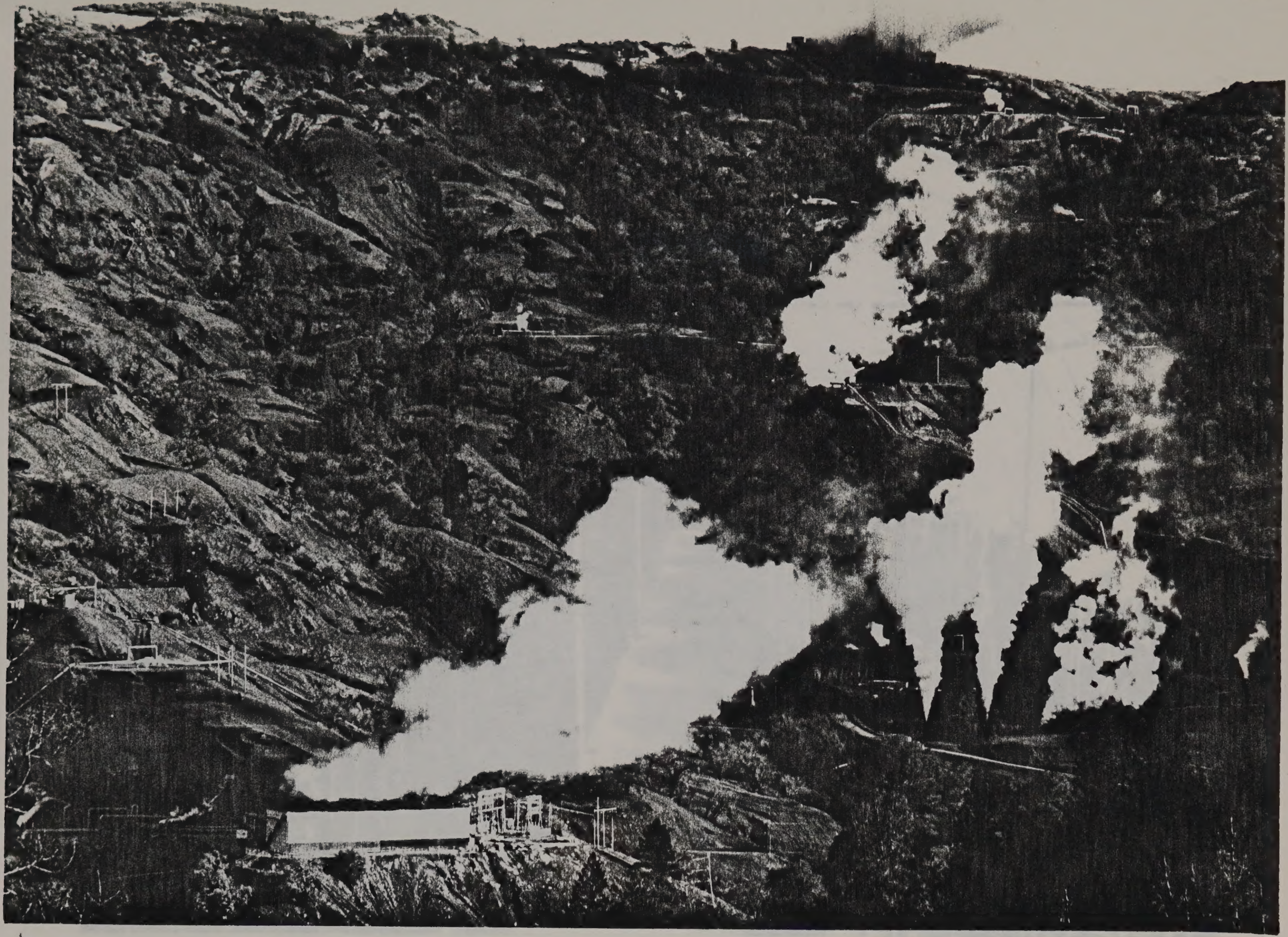


Power plant - 110 MW power plant at The Geysers, California. The geothermal turbine generators are housed in building at right. Cooling towers are at left.

Plate 10

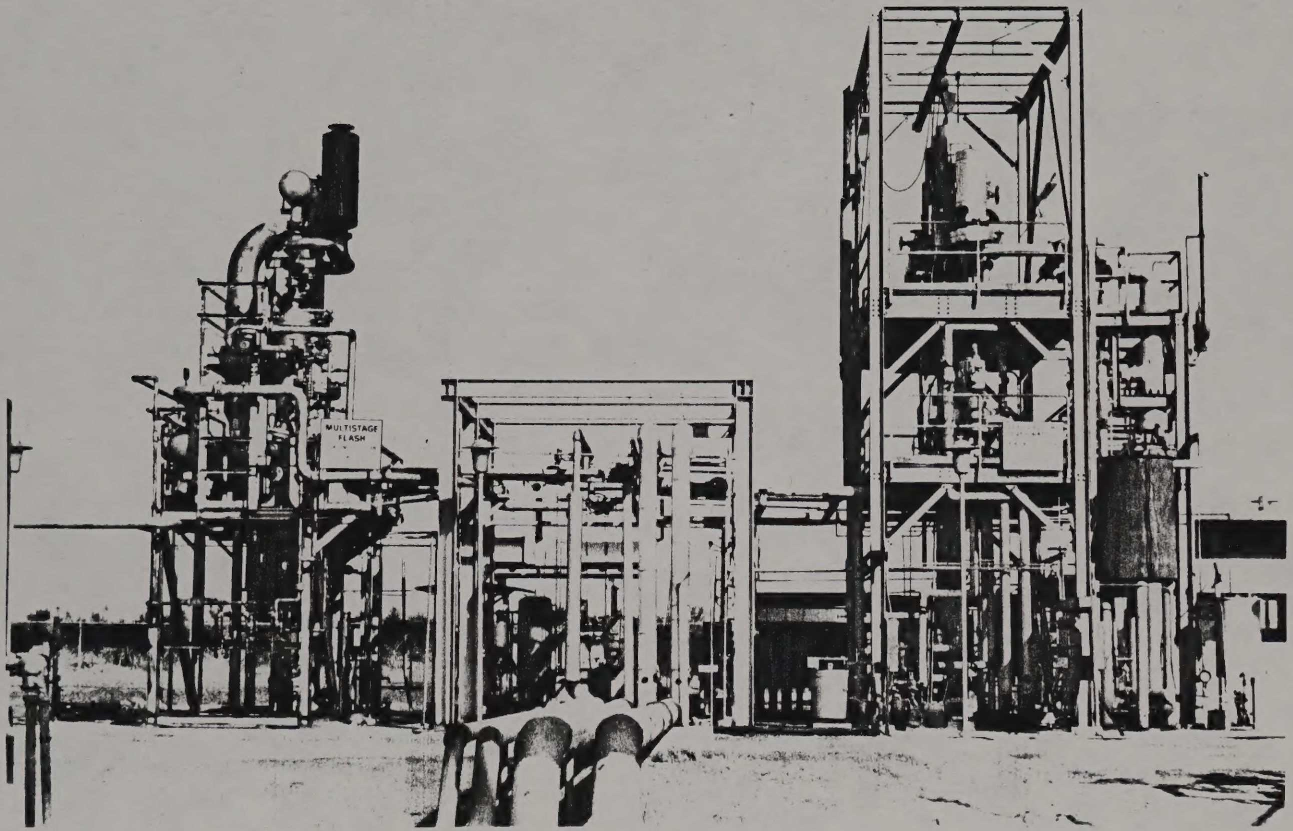


Geothermal field development - Steam from the well (lower right) is transmitted through pipelines to the power plant. Note the expansion loops in the pipelines.



The Geysers field - A panoramic view of The Geysers geothermal field in northern California. This is the largest commercial geothermal development in the world. (Photo-Pacific Gas and Electric Co.)

Space heating - Geothermal energy heats this greenhouse in Wendel-Amedee, California. The tomatoes are grown in a solution of geothermal water and plant nutrients.



Desalination plant - the U. S. Bureau of Reclamation is desalting geothermal brines and returning upgraded water to the Colorado River.

Plate 14

BLM Library
Denver Federal Center
Bldg. 50, OC-521
P.O. Box 25047
Denver, CO 80225